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ORIGINAL PAPER

Assessing the effect of governing parameters of bearing capacity determination of small piled rafts on clay soil

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Abstract

In the present study, a small piled raft foundation has been simulated numerically through PLAXIS 3-D software. The objective of this study was to investigate the effect of governing parameters such as pile length, pile spacing, pile diameter, and number of piles on the settlement and load-bearing behavior of piled raft, so as to achieve the optimum design for small piled raft configurations. An optimized design of a piled raft is defined as a design with allowable center and differential settlements and satisfactory bearing behavior for a given raft geometry and loading. The results indicated that, with increase in pile length, pile spacing, pile diameter, and number of piles, both the center settlement ratio and differential settlement ratio decreased. The load-bearing capacity of piled raft increased with increase in pile length, pile spacing, pile diameter, and number of piles. Furthermore, the percentage load carried by the piles increased as the pile length, pile spacing, pile diameter, and number of piles increased. The bending moment and shear force in corner pile are noted to be more, and they decreased towards the center pile. With increase in pile length, the maximum raft bending moment decreased, whereas the maximum shear force in the raft increased. Further, with increase in pile spacing, pile diameter, and number of piles, the maximum bending moment and maximum shear force in the raft increased. The optimum parameters for the piled raft foundation can be selected efficiently with the consideration of maximum bending moment and maximum shear force while designing the piled raft foundation. Thus, the results of this study can be used as guidelines for achieving optimum design for small piled raft foundation.

Keywords Piled raft · Settlement ratio · Numerical modeling · Clay

Introduction

Foundation is the most important part of the structure, and hence, it should be analyzed and designed in order to provide safety, reliability, and serviceability of the structure. If the shear strength of clay soil is very poor, long load-bearing piles are required to transfer the entire load to deeper and stiffer soil layers. Moreover, if the shear strength of clay soil is adequate, then load can be supported by the raft foundation. However, when the clay layer has intermediate strength, raft foundation may not be feasible, as the bearing capacity may not be adequate, or settlements may be excessive. In such cases, where a raft foundation alone does not satisfy the settlement and bearing criteria, a limited number of piles can be added to enhance its settlement performance and the load-bearing capacity (Maharaj and Gandhi 2004).

The piled raft can be classified into two categories, as "small piled raft" when the raft width is lesser than the pile length ($B_r < L_p$), and as "large piled raft" when the raft width is greater than the pile length ($B_r > L_p$) (Viggiani 2001). In a small piled raft, the primary reason to add the piles is to achieve a sufficient factor of safety against bearing failure. However, in a large piled raft, piles are added essentially to reduce the settlement. The piled raft has been used for supporting a high rise buildings and offshore structures because it is very efficient in reducing settlement and improving the load-bearing capacity of soil. A few successful applications of piled rafts on soft clay were reported by Sales et al. (2010), and Russo et al. (2013. Ahmed et al. (2014) evaluated the soil-foundation-structure interaction of buildings

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founded on piled raft foundation through PLAXIS 3-D software. They reported that the interaction of building foundation-soil field and superstructure was remarkable effect on the structure.

Nguyen et al. (2014) conducted the parametric study for optimal design of large piled raft foundations on sandy soil through centrifuge test. The study showed that the concentrated pile arrangement method can help to considerably reduce the total and differential settlements as well as the induced bending moments of the raft. Akl et al. (2014) studied the effect of changing configurations and lengths of piles on piled raft foundation behavior on clay soil through FLAC 3-D software. For the same number of piles, the change in piles distribution over the raft area was a slight effect on the piled raft average settlement, while it had a considerable effect on the piled raft differential settlement. Johari et al. (2017) carried reliability analysis of seismic ultimate bearing capacity of strip footing by slip lines method coupled with random field theory. They compared probability density functions of seismic and static bearing capacities to each other. The predicted probability density function (PDF) of the seismic bearing capacity by slip line method is verified, with those of the Terzaghi equation and Monte Carlo simulation (MCs).

Johari and Sabzi (2017) presented reliability-based analysis of strip footing settlement by stochastic finite element method (SFEM). The stochastic response surface method (SRSM) and random finite element method (RFEM) are used as two formulation of SFEM. It was observed that the results of SRSM are close to RFEM; however, the consumed time in RFEM is at most 50 times longer than SRSM. Using the faster method, SRSM, it is concluded that considering the spatial variability of soil parameters in stochastic analysis is necessary. Johari and Talebi (2021) extended the application of random fields to a stochastic analysis of a piled raft foundation embedded into an elastoplastic soil. The stochastic analysis showed that implementation of the uncertainties of soil parameters leads to more influence on the raft differential settlement compared to the other responses. Variation of the horizontal and vertical correlation length has a more considerable effect on the coefficient of variation (COV) of the bored piles' responses compared to those of the raft. Based on the COV, it is demonstrated that the heterogeneity of the soil has more influence on the raft.

Lee et al. (2010) carried a three-dimensional analysis of bearing behavior of piled raft on soft clay with ABAQUS 3-D software. They reported that the use of a limited number of piles, strategically located, might improve both bearing capacity and the settlement performance of the raft. Cho et al. (2012) studied the settlement behavior of piled raft in soft and stiff clay soils for quantifying the reduction of the average and differential settlements. The study indicated that the variation of settlement reduction ratio of soft clay was relatively greater than that of stiff clay. In addition to this, some other numerical studies were carried out on the analysis of a piled raft in clay soil using a 3-D finite element method (Sanctis and Mandolini 2006; Oh et al. 2009).

However, only a few studies have been carried out to examine the effect of governing parameters such as pile length (L_p), pile spacing (S_p), pile diameter (d_p), and number of piles (N_p), on the settlement and load-bearing behavior of small piled raft foundation on a clay soil. Moreover, the role of above governing parameters in optimal design of a small piled raft foundation is less well documented and needs to be investigated. The objective of present study is to investigate the effect of the above governing parameters on the settlement and load-bearing behavior of piled raft by means of numerical analysis, so as to achieve the optimum design for small piled raft configurations. The optimization of piled raft geometry involves the determination of optimum values of governing parameters, so that the maximum and differential settlements are lower than the allowable values by the least margin, and the load intensity below the raft portion of the piled raft is lower than the safe bearing capacity (q_s) of the unpiled raft.

Numerical modeling

In the present study, the behavior of small piled raft was examined by PLAXIS 3-D numerical analysis. The model consists of unaffected soil domain, piled raft geometry, and the applied load (q) of 150 kPa. The soil was modeled with 10-node tetrahedral elements and as following the elastic-perfectly plastic Mohr–Coulomb model. Mohr–Coulomb model requires lesser number of input parameter of soil, and also these parameters can be easily found in the laboratory. The parameters required for modeling consisted of cohesion, angle of internal friction, Young's modulus, and Poisson's ratio. As per the Mohr–Coulomb failure criteria, the yielding or failure takes place in the soil mass as the mobilized shear stress at any plane becomes equal to the shear strength of soil.

A raft was placed on the ground surface of soil and water table assumed to be located at a ground surface. The raft and piles were modeled with 5-node triangular plate element and 4-node line elements, respectively. The material of raft and piles were considered to be linear elastically. The piles and raft was connected by rigid connection. The lateral boundaries were placed at a distance of twice the width of raft from the raft edge and restrained against horizontal translation to allow downward movement of the soil. The bottom most horizontal boundary was placed at a depth of twice the width of raft plus maximum length of pile used in the study (L_{pmax}) and restricted from both horizontal and vertical translations. The globally fine mesh has been selected for the entire soil domain; however, relatively finer mesh was chosen near the structural elements. Figure 1 show the typical finite element mesh used in the present study.

Model validation

The present finite element model in PLAXIS 3-D has been validated using an example reported by Poulos (2001a). In this example, the soil has been characterized by modulus of elasticity ($E_{s)}=20$ MPa and Poisson's ratio of (ν_s) = 0.3. Pile and raft Young's modulus, $E_p = E_r = 30$ GPa have been considered. The comparison of the results of the present study and reported results is shown in Fig. 2. It can be seen that there is a good agreement with the reported results for different number of piles.

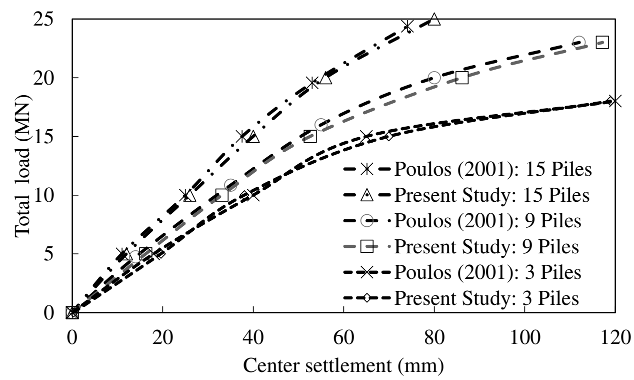

Fig. 2 Comparison of load-settlement behavior between present method and method used by Poulos (2001a) for different number of piles

Parametric study

In the current study, a square unpiled raft foundation system of 15 m width (B_r) and thickness (t_r) of 1.5 m, resting on soft clay, has to transmit the uniformly distributed load (*UDL*) from the superstructure 150 kPa. The physical and mechanical properties of soil, raft, and piles are tabulated in Table 1. The values of E_s, ν_s, E_r, t_r, and E_p have been selected from the guidelines given by Viggiani (2001). Based on the vertical settlement of the raft, the center settlement ratio (W_{ratio}) and differential settlement ratio (ΔW_{ratio}) can be determined. The W_{ratio} is defined as the ratio of center settlement of raft (W_c) to the allowable maximum settlement (*AMS*) of the raft. The ΔW_{ratio} is considered as the ratio of differential settlement of raft (W_{c-e}) to the allowable maximum differential settlement (*AMDS*) of the raft. The W_{c-e} is defined as the difference between W_c and edge settlement of the raft (W_e) to

$$W_{ratio} = \frac{W_C}{AMS} \tag{1}$$

$$\Delta W_{\text{ratio}} = \frac{W_{c-e}}{AMDS} \tag{2}$$

As per IS 6403–1981, the ultimate bearing capacity of raft (q_{ur}) foundation placed at the soil surface is calculated by the following formula:

$$q_{ur} = c_u.N_c.S_c.d_c.i_c \tag{3}$$

where $c_u = 25\ kPa$, $N_c = Bearing\ capcity\ factor = 5.14$, $S_c = Shape\ factor = 1.3$, $d_c = Depth\ factor = 1$, $i_c = Inclination\ factor = 1$

$$\therefore q_{ur} = c_u \times 5.14 \times 1.3 \times 1 \times 1 = 6.68.c_u = 6.68 \times 25 = 167.05\ kPa$$

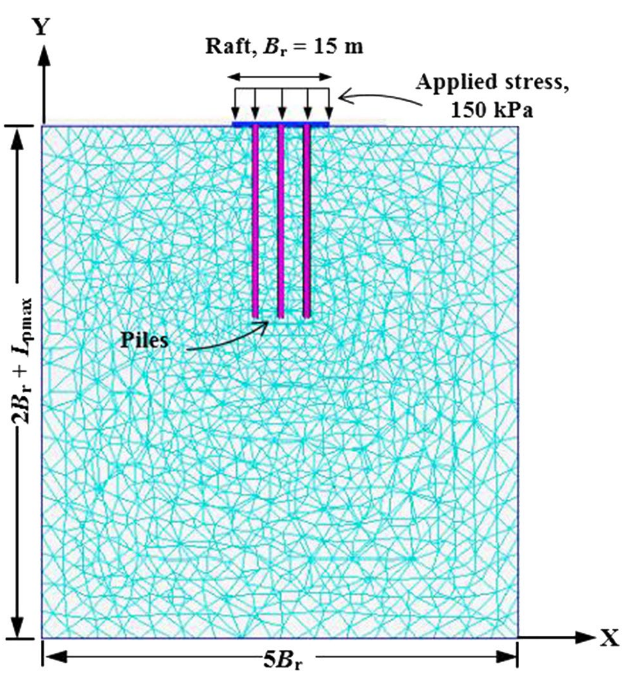

Fig. 1 Typical finite element mesh used in the parametric study

Table 1 Material properties used in the numerical modeling

Material	Properties	Unit	Values
Soil	Unsaturated unit weight, γ_{unsat}	kN/m^3	16
	Saturated unit weight, γ_{sat}	kN/m^3	17
	Young's modulus, E_s	MPa	25
	Poisson's ratio, ν_s	-	0.495
	Undrained cohesion, c_u	kPa	25
	Angle of internal friction, φ	°	0
Raft	Young's modulus, E_r	GPa	25
	Poisson's ratio, ν_r	-	0.25
Pile	Young's modulus, E_p	GPa	25
	Poisson's ratio, ν_p	-	0.25

By considering factor of safety ($F.O.S$) equal to 2.5, the calculated safe bearing capacity (q_s) of the raft is as follows.

$$q_s = \frac{q_{ur}}{F.O.S} = \frac{167.05}{2.5} = 66.82 \cong 67\ kPa \quad (4)$$

As per IS 1904–1986, the AMS of the raft foundation is 125 mm, whereas the $AMDS$ is 49.5 mm ($0.0033{*}B_r$). If only unpiled raft of any t_r is considered, it possesses inadequate q_s of 66.8 kPa at $q = 150$ kPa. In addition to this, at $q = 150$ kPa, the unpiled raft of $t_r = 1.5$ m undergoes excessive W_c (913 mm) and $W_{c\text{-}e}$ (164 mm) compared to the allowable values (Table 2).

It can also be noted that at W_c of 125 mm, the maximum q that can be carried by the unpiled raft is 129 kPa for t_r of 1.5 m. Therefore, the piles have to be added to the raft so as to reduce the settlements and to enhance the load-bearing capacity of the unpiled raft. The effects of different parameter such as L_p, S_p, d_p, and N_p on the settlement and load-bearing behavior were studied through by 3-D numerical modeling. Figure 3 shows the typical layout of piled raft foundation for 3 × 3 pile group. The details of different small piled raft configurations ($B_r < L_p$) included in this study are tabulated in Table 3.

The purpose of the parametric study is to achieve the optimization of L_p, S_p, d_p, and N_p on the basis of settlement criteria and the bearing capacity criteria. The results are plotted in terms of settlement ratio, load-settlement behavior, and percentage load carried by the piles.

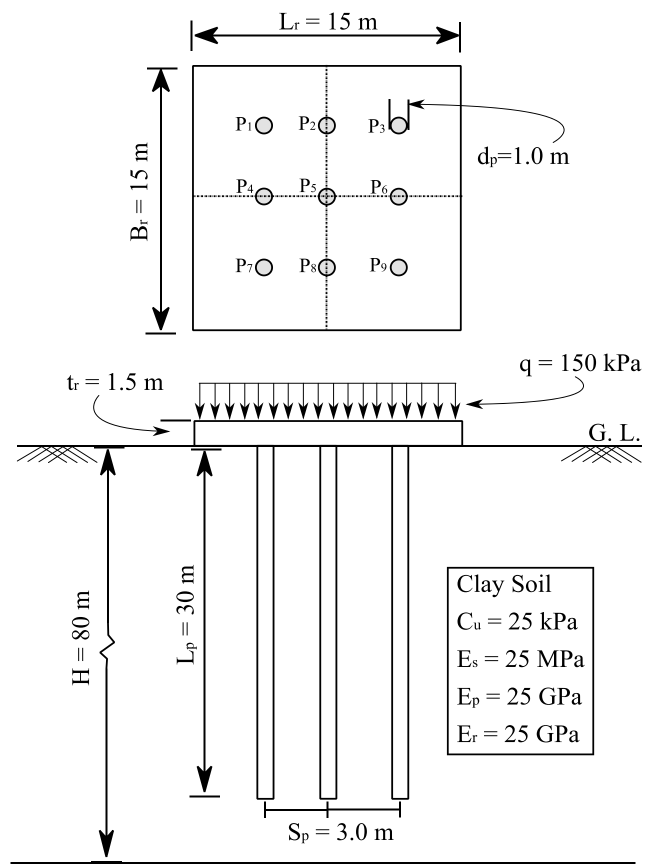

Fig. 3 Typical layout of piled raft foundation with 3 × 3 pile group

Results and discussion

Check for settlement criteria

Effect of pile length (L_p)

The effect of L_p on the W_{ratio} for different pile group configurations is presented in Fig. 4. For any pile group, the pile lengths that satisfy the settlement criterion are found to be below the horizontal line with arrow head drawn at W_{ratio} or ΔW_{ratio} of 1. It can be observed that with increase in L_p/d_p ratio from 15 to 50, the W_{ratio} decreased for any configuration. Moreover, with increasing S_p, the pile group action might be diminishing and due to which the W_{ratio} decreased. Thus, for 2 × 2 pile group, the required minimum L_p was 20 m for pile spacings of 4 m and 5 m, and the corresponding total length of pile (L_{ptotal}) was 80 m. Similarly, for 4 × 4 pile group, the minimum L_p that satisfied the settlement criterion was 15 m with S_p of 4 m, and the corresponding L_{ptotal} was 240 m. Therefore, a minimum of four piles with L_{ptotal} of 80 m ($L_p = 20$ m and $N_p = 4$) and S_p of 4 m was sufficient to satisfy the W_{ratio} criteria. Seo et al. (2003) carried the parametric study of the piled raft by PLAXIS 2-D software and reported that the total settlement of piled raft in clay soil decreased as the pile length increased. Therefore, the finding of the present study is consistent with the reported results.

Table 2 Bearing capacity and settlements for unpiled raft ($t_r = 1.5$ m)

q (kPa)	q_s (kPa) as per IS 6403–1981	Allowable settlements as per IS 1904–1986 (mm)		Measured settlements using PLAXIS 3-D (mm)	
		AMS	$AMDS$	W_c	$W_{c\text{-}e}$
150	66.8	125	49.5 ($0.0033{*}B_r$)	913	164

Table 3 Details of different piled raft configurations

Series	Pile group	Parametric values (m)
1	2 × 2	$L_p = 15, 20, 30, 40, 50$
2	3 × 3	$S_p = 3, 4, 5$
3	4 × 4	$d_p = 0.5, 1.0, 1.5$
		$t_r = 1.5$

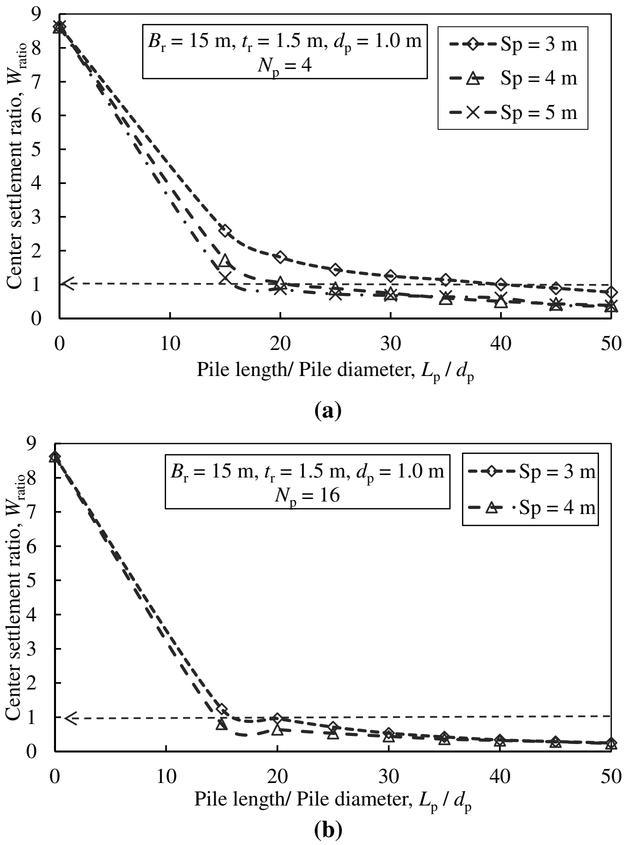

Fig. 4 Center settlement ratio versus L_p/d_p ratio: **a** 2×2 pile group and **b** 4×4 pile group

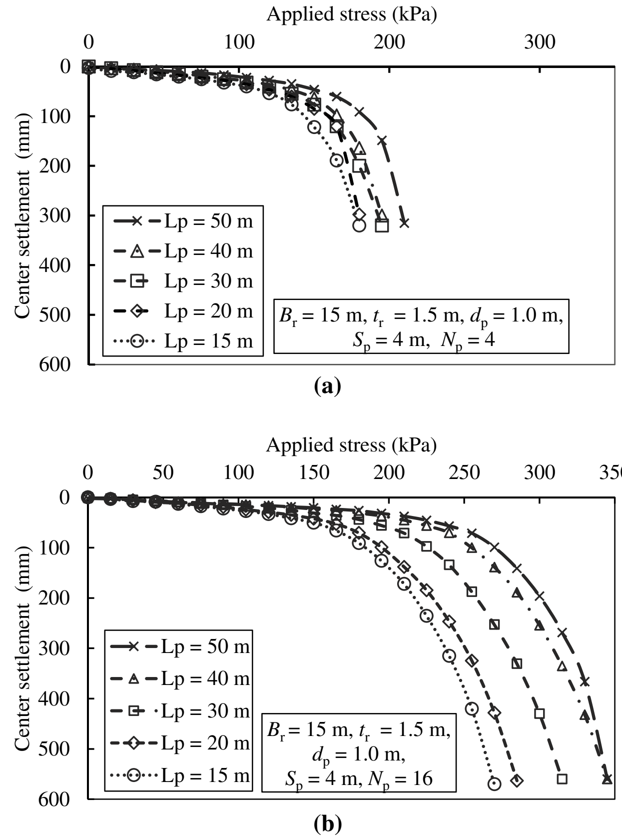

Fig. 5 Load-settlement behavior for different pile lengths: **a** 2×2 pile group and **b** 4×4 pile group

The effect of L_p on the load-settlement behavior of piled raft is shown in Fig. 5. It can be observed that the load-bearing capacity of the piled raft increased with increase in L_p, and the W_c measured at the center point on the raft decreased with the increase in L_p. Sinha and Hanna (2016) reported that the load carrying capacity of the piled raft increased and the settlement measured at the center point on the raft decreased with the increase of the pile length. The maximum W_c values at 150 kPa load for 15 m pile length were 273 mm, 132 mm, and 107 mm, respectively, for the 2×2, 3×3, and 4×4 pile groups.

Effect of pile spacing (S_p)

The effect of S_p on the W_{ratio} for different pile group configurations is shown in Fig. 6. For any pile group, the pile spacings that satisfy the settlement criterion are found to be below the horizontal line with arrow head drawn at W_{ratio} or ΔW_{ratio} of 1. It can be seen that with increase in S_p/d_p ratio from 3 to 5, W_{ratio} decreased for the 4×4 configuration. As the S_p increased, there might be uniform distribution of load among the piles, due to which W_{ratio} decreased. However, for the 2×2 configuration, the W_{ratio} remained constant as S_p/d_p ratio changed from 3 to 4, and thereafter, the W_{ratio} decreased at S_p/d_p ratio of 5. This behavior might be attributed to the transition of pile group action to the individual pile action. For the 2×2 pile group, the pile spacings of 3 m and 4 m satisfied the settlement criteria for pile lengths of 40 and 50 m. Similarly, for 4×4 pile group, the S_p of 4 m satisfied the settlement criteria for L_p of 30 m. Therefore, a minimum of four piles with L_{ptotal} of 160 m (L_p = 40 m and N_p = 4) and S_p of 4 m was sufficient to satisfy the W_{ratio} criteria.

Effect of number of piles (N_p)

The effect of the N_p on the W_{ratio} of piled raft foundations is shown in Fig. 7. The total numbers of piles that satisfy the settlement criterion are found to be below the horizontal line with arrow head drawn at W_{ratio} or ΔW_{ratio} of 1. From this figure, it can be observed that with increase in N_p from 4 to 16, W_{ratio} decreased. Thus, a minimum nine piles with L_{ptotal} of 135 m (L_p = 15 m and N_p = 9) was sufficient to satisfy the W_{ratio} criteria.

Figure 8 shows the variation of ΔW_{ratio} versus N_p for different pile lengths. It can be seen that with increase in N_p from 4 to 16, ΔW_{ratio} decreased initially, and then it

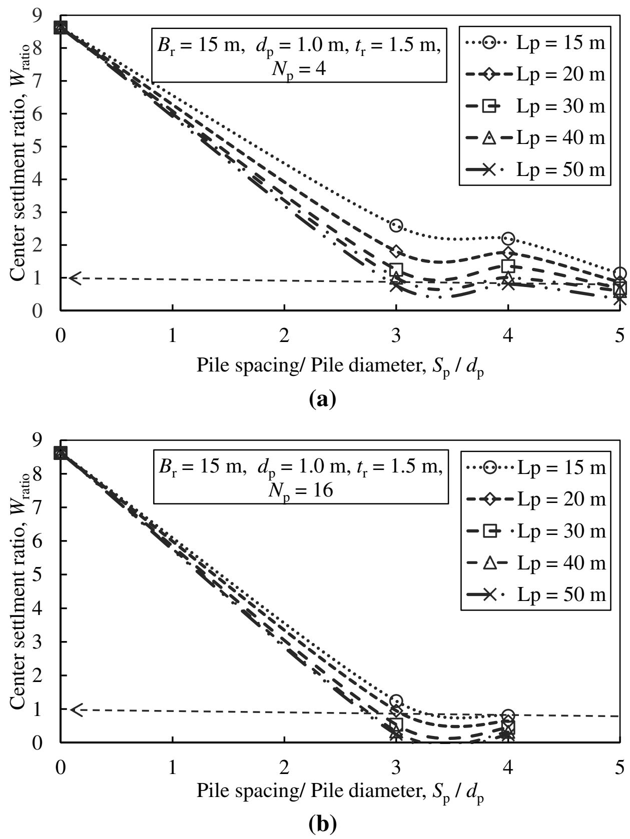

Fig. 6 Center settlement ratio versus S_p/d_p ratio: **a** 2×2 pile group and **b** 4×4 pile group

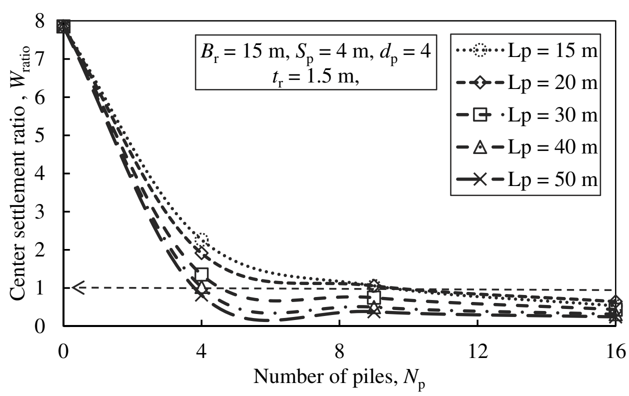

Fig. 7 Center settlement ratio versus number of piles

remain constant for 2×2 pile group. Moreover, the similar trends were observed for the other pile groups (3×3 and 4×4). Therefore, a minimum of 15 m L_p with any N_p can be used to satisfy the ΔW_{ratio} criterion. Thus, a minimum of four piles with L_{ptotal} of 60 m (L_p = 15 m and N_p = 4) was sufficient to satisfy the ΔW_{ratio} criteria.

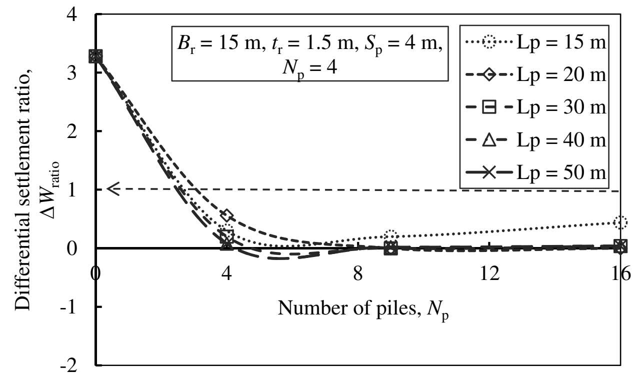

Fig. 8 Differential settlement ratio versus number of piles

Check for bearing capacity

Effect of pile length (L_p)

Table 4 shows the comparison of load carried by individual piles (q_p) and the load carried by piles as a percentage of its ultimate capacities ($q_{\%u}$) for different pile lengths. It can be noted that the corner pile carried the highest load followed by the edge pile and the center pile. Moreover, it was also observed that all the piles with different lengths were loaded to almost ~ 50% of its ultimate capacity. The ultimate capacity (q_{up}) of a pile of L_p equal to 15 m, 20 m, 30 m, 40 m, and 50 m with 1 m d_p was calculated to be 1354.12 kPa, 1746.62 kPa, 2531.62 kPa, 3316.62 kPa, and 4101.62 kPa, respectively. The q_{up} for a L_p of 30 m and 1 m d_p is illustrated as follow.

$$q_{up} = \left(c_u N_c A_b + \alpha c_u A_s\right) \tag{5}$$

where $c_u = 25\ kPa$, $N_c = 9$, $A_b = area\ of\ base\ of\ pile = 0.785 \times 1^2 = 0.785m^2$,

$\alpha = Adhesionfactor = 1$

$\boldsymbol{A_s = surface\ area\ of\ pile = 3.14 \times 1 \times 30 = 94.2m^2}$**,**

$\therefore q_{up} = (25 \times 9 \times 0.785 + 1 \times 25 \times 94.2) = 2531.62\ kPa$

Effect of pile spacing (S_p)

Table 5 shows the comparison of q_p and $q_{\%u}$ for different pile spacings. It can be seen that for any S_p, the load carried by different piles increased in the following order: corner pile, edge pile, and center pile. Moreover, it was

Table 4 Comparison of q_p and $q_{\%u}$ for different pile lengths ($S_p = 4$ m, $d_p = 1.0$ m, and $N_p = 9$)

L_p (m)	Load	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
15	q_p (kN)	713	647	711	689	709	683	711	710	709
	$q_{\%u}$ (%)	53	48	53	51	52	50	52	52	52
20	q_p (kN)	894	847	928	926	884	899	925	886	927
	$q_{\%u}$ (%)	51	48	53	52	50	51	52	50	53
30	q_p (kN)	1278	1258	1240	1224	1243	1238	1248	1305	1280
	$q_{\%u}$ (%)	50	50	49	48	49	49	49	52	51
40	q_p (kN)	1659	1608	1653	1591	1591	1622	1691	1608	1658
	$q_{\%u}$ (%)	49	48	49	47	47	48	50	48	49
50	q_p (kN)	2015	1923	1943	2010	1994	1892	1837	1935	1990
	$q_{\%u}$ (%)	49	47	47	49	49	46	45	47	49

Table 5 Comparison of q_p and $q_{\%u}$ for different pile spacings ($L_p = 30$ m, $d_p = 1$ m, and $N_p = 9$)

S_p (m)	Load	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
3	q_p (kN)	1288	1210	1249	1236	1216	1187	1231	1230	1260
	$q_{\%u}$ (%)	51	48	49	49	48	47	49	49	50
4	q_p (kN)	1258	1278	1240	1224	1243	1238	1248	1305	1280
	$q_{\%u}$ (%)	50	50	49	48	49	49	49	52	51
5	q_p (kN)	1292	1319	1311	1267	1229	1197	1329	1324	1324
	$q_{\%u}$ (%)	51	52	52	50	49	47	52	52	52

Table 6 Comparison of q_p and $q_{\%u}$ for different pile diameters ($L_p = 30$ m, $S_p = 4$ m, and $N_p = 9$)

d_p (m)	Load	P_1	P_2	P_3	P_4	P_5	P_6	P_7	P_8	P_9
0.5	q_p (kN)	765	766	769	762	771	772	769	773	774
	$q_{\%u}$ (%)	63	63	63	62	63	63	63	63	63
1	q_p (kN)	1258	1278	1240	1224	1243	1238	1248	1305	1280
	$q_{\%u}$ (%)	50	50	49	48	49	49	49	52	51
1.5	q_p (kN)	1484	1512	1510	1481	1496	1500	1561	1460	1502
	$q_{\%u}$ (%)	38	38	38	38	38	38	40	37	38

also observed that with increase in S_p, the $q_{\%u}$ remained constant approximately.

Effect of pile diameter (d_p)

The effect of pile diameter on percentage load carried by piles is shown in Table 6. It can be seen that for every d_p, the load carried by different piles increased in the following order: corner pile, edge pile, and center pile. In addition to this, it was noted that with increase in d_p at constant L_p, the $q_{\%u}$ decreased.

Effect of number of piles (N_p)

Figure 9 shows the variation of percentage load carried by the piles versus the number of piles. As the N_p increased, the percentage load carried by the piles increased for all L_p. The load carried by 30 m pile varies from 14.40 to 54.69% as the N_p increased from 4 to 16. El-Garhy et al.

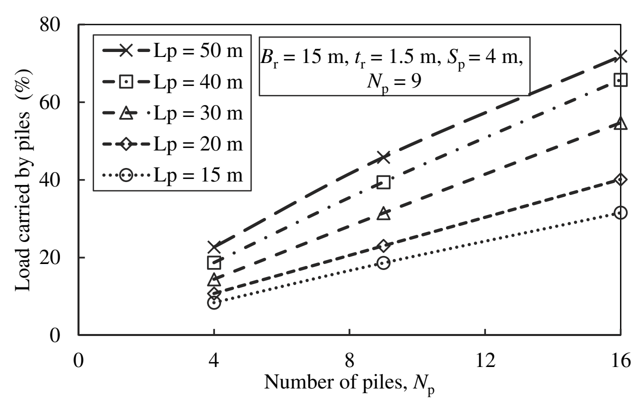

Fig. 9 Percentage load carried by piles versus N_p

(2013) reported that the proportion of load carried by piles increased as the number of piles increased, and inversely the proportion of load carried by raft decreased as the number of piles increased.

Thus, the piled raft configuration which satisfied the settlements criteria (W_{ratio} and ΔW_{ratio}) may or may not provide the necessary $q_s = 67$ kPa, and hence, it is important to check the possible configurations which will satisfy both the criteria. Table 7 shows the total load carried by the piles (q_{ptotal}), load carried by the raft (q_r), measured safe bearing capacity of raft from PLAXIS 3-D (q_m), and W_c for different pile groups with variations of S_p, and N_p. It can be seen that both the settlement criteria and bearing capacity criteria can be fulfilled for a minimum L_{ptotal} is equal to 480 m ($L_p = 30$ m, $N_p = 16$). Therefore, out of the piled raft configuration which satisfied both the settlement and bearing capacity criteria can be selected as the optimum configuration for the present study. Thus, based on the settlements criteria (W_{ratio} and ΔW_{ratio}) and bearing capacity criteria ($q_m \leq 67$ kPa), the piled raft configuration with $L_p = 30$ m, $S_p = 4$ m, $d_p = 1$ m, $N_p = 16$, and $t_r = 1.5$ may be selected as the optimum configuration for the present study.

Bending moment (M) and shear force (τ)

The maximum bending moment (M_{max}) and maximum shear force (τ_{max}) developed in the raft foundations are considered as crucial entity for designing the required reinforcing steel. The magnitudes of M_{max} and τ_{max} in raft vary with variation of L_p, S_p, d_p, and N_p. Table 8 shows the M_{max} and τ_{max} for different piled raft parameters. It can be seen that, with increase in L_p, the M_{max} decreased and τ_{max} increased. Moreover, with increase in S_p, d_p, and N_p, the M_{max} and τ_{max} increased. Poulos (2001b) reported that the maximum bending moment in the raft increases with increases in raft thickness and number of piles. Therefore, the optimum parameters for the piled raft foundation can be selected efficiently with the consideration of M_{max} and τ_{max} while designing the piled raft foundation.

Table 8 Effect of different piled raft parameters on τ_{max} and M_{max}

Parameters	Values (m)	M_{max} (kN-m/m)	τ_{max} (kN/m)
L_p (m)	15	668	287
	20	559	259
	30	377	299
	40	291	379
	50	212	443
S_p (m)	3	160	279
	4	377	299
	5	616	327
d_p (m)	0.5	346	224
	1	377	299
	1.5	527	411
N_p	4	260	257
	9	377	299
	16	771	488

Conclusions

The study considered a framework for the optimum design in terms of maximum settlement, differential settlements, and load-bearing capacity of piled raft. Based on the results, following conclusions are presented.

1. With increase in L_p/d_p ratio from 15 to 50 by keeping $d_p = 1$ m, the W_{ratio} and ΔW_{ratio} decreases for all the pile group arrangements; moreover, the percentage load carried by the piles increases. The minimum of four piles with L_{ptotal} of 80 m ($L_p = 20$ m and $N_p = 4$) and S_p of 4 m is sufficient to satisfy the W_{ratio} criteria. Similarly a minimum of four piles with L_{ptotal} of 60 m ($L_p = 15$ m and $N_p = 4$) is sufficient to satisfy the ΔW_{ratio} criteria. The load-bearing capacity of piled raft increases with increase in L_p and the W_c decreases with the increase in L_p. The W_c is lower for a greater L_p for any pile group. For any L_p, the largest pile loads are concentrated at the corner of the pile group, and it decrease towards the center of the group.

Table 7 Load intensity and center settlement below the raft for different piled raft configuration

d_p (m)	t_r (m)	S_p (m)	N_p	L_p (m)	L_{ptotal} (m)	q_{ptotal} (kN)	q_r (kN)	q_m (kPa)	W_c (mm)
1	1.5	3	3×3	50	450	16,390	17,360	79.66 (> q_s)	49 (< *AMS*)
			4×4	30	480	19,249	14,501	66.54 (< q_s)	67 (< *AMS*)
			5×5	20	500	21,072	12,678	58.17 (< q_s)	78 (< *AMS*)
		4	3×3	50	450	17,539	16,211	74.39 (> q_s)	48 (< *AMS*)
			4×4	20	320	13,974	19,776	90.74 (> q_s)	80 (< *AMS*)
				30	480	19,963	13,787	63.26 (< q_s)	55 (< *AMS*)
		5	3×3	50	450	18,429	15,321	70.30 (> q_s)	47 (< *AMS*)

2. With increase in S_p/d_p from 3 to 5, the W_{ratio} decreases for all pile groups of any L_p; moreover, the percentage load carried by the piles increases. However, the increase is noted to be minimal beyond 4 m spacing. A minimum of four piles with L_{ptotal} of 160 m ($L_p = 40$ m and $N_p = 4$) and S_p of 4 m is sufficient to satisfy the W_{ratio} criteria. The load-bearing capacity of piled raft increases with increase in S_p and the W_c decreases with the increase in S_p. For any S_p, the largest pile loads are concentrated at the corner of the pile group, and it decrease towards the center of the group.
3. With increase in N_p, the W_{ratio} decreases and the percentage load carried by the piles increases. Also as the N_p increases, the ΔW_{ratio} decreases initially and then remains constant for all pile groups. A minimum nine piles with L_{ptotal} of 135 m ($L_p = 15$ m and $N_p = 9$) is sufficient to satisfy the W_{ratio} criteria. Similarly, a minimum of four piles with L_{ptotal} of 60 m ($L_p = 15$ m and $N_p = 4$) is sufficient to satisfy the ΔW_{ratio} criteria. The load-bearing capacity of piled raft increases with increase in N_p and the W_c of the raft decrease with the increase in N_p.
4. Based on the settlements criteria (W_{ratio} and ΔW_{ratio}) and bearing capacity criteria ($q_m \leq 67$ kPa), the piled raft configuration with $L_p = 30$ m, $S_p = 4$ m, $d_p = 1$ m, and $N_p = 16$ may be selected as the optimum parameter for the present study.
5. The τ and M are observed to be higher in corner pile and they decreases towards the center pile. With increase in L_p, the M_{max} decreases and τ_{max} increases. Moreover, with increase in S_p, d_p, and $N_{p,}$ the, M_{max} and τ_{max} increases.

Declarations

Conflict of interest The authors declare that they have no competing interests.

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